Pole inflation and its realizations

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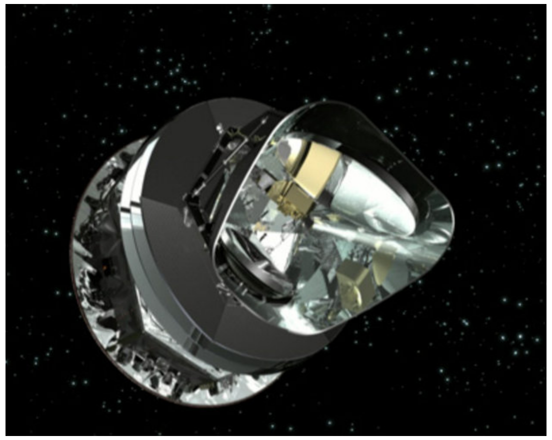
2025 Joint Workshop of FKPPN & TYL/FJPPN
LS2N, Nantes, France, May 16, 2025.

Finding New Physics: From Earth to Sky



- New Physics for Higgs and Hierarchy Problem: supersymmetry, warped extra dimension, clockwork, relaxion, etc.
- New Physics for Dark Matter: WIMP, FIMP, SIMP, axion, new productions/detections.
- New Physics for Flavor Physics: fermion masses/mixing, flavor puzzles from rare decays, magnetic/electric dipole moments.

FNES Collaboration

French team

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Yann Mambrini
(IJCLab, Orsay)

Simon Clery
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→ TUM, Germany

Mathieu Gross
(PhD, IJCLab, 2023~)

Korean team

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CHUNG-ANG UNIVERSITY · 1918

Hyun Min Lee
(CAU)

Adriana Menkara
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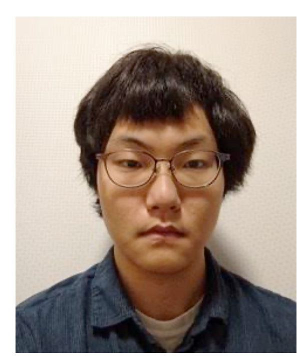
→ DESY, Germany



Seong-Sik Kim
(PhD, CAU, 2022~2025)

→ Chungnam National Univ

FNES Collaboration

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Junior positions from our team

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CHUNG-ANG UNIVERSITY · 1918

Mathias Pierre
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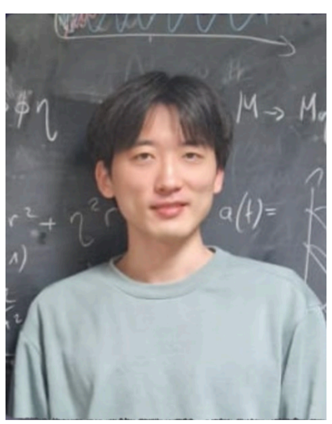
→ DESY (Staff), Germany

Kunio Kaneta
(Postdoc, KIAS, 2020~2021)

→ Faculty, Niigata Univ, 2024~

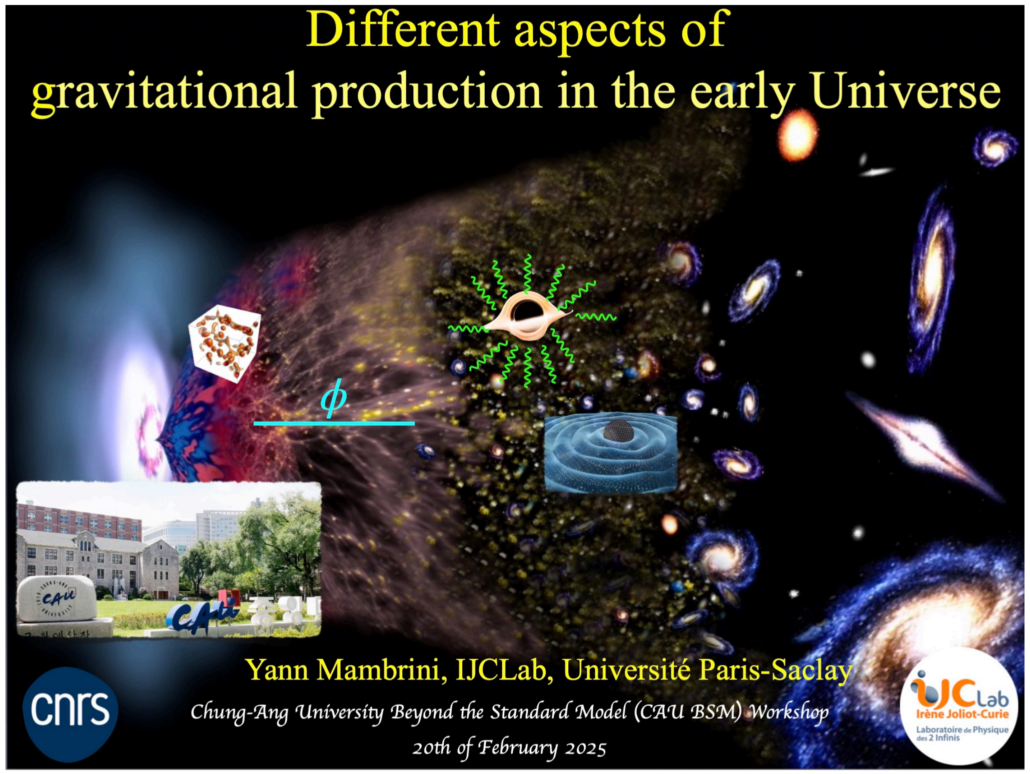


Jong-Hyun Yoon
(postdoc, IJCLab, 2022~2024)

NRF 한국연구재단

→ Sejong fellow, National Research Foundation,
Chungnam National Univ, Korea
(Prestigious fellowship for 5 years)

2024-2025 activities



Korea: funded by NRF, IBS

CAU BSM workshop, 17-21 Feb, 2025

Invited talk by

Yann Mambrini (on zoom)

France: funded partly by FKPPL

Astroparticle Symposium, Saclay,
25 - 29 Nov, 2024

Invited talks by

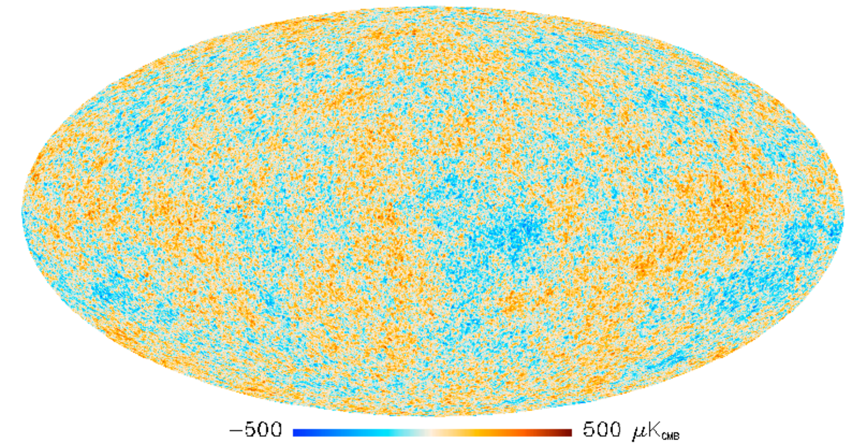
HML, Adriana Menkara

Outline

- Introduction
- Pole inflation and particle physics
- Pole inflation in Weyl gravity
- Conclusions

Cosmic inflation

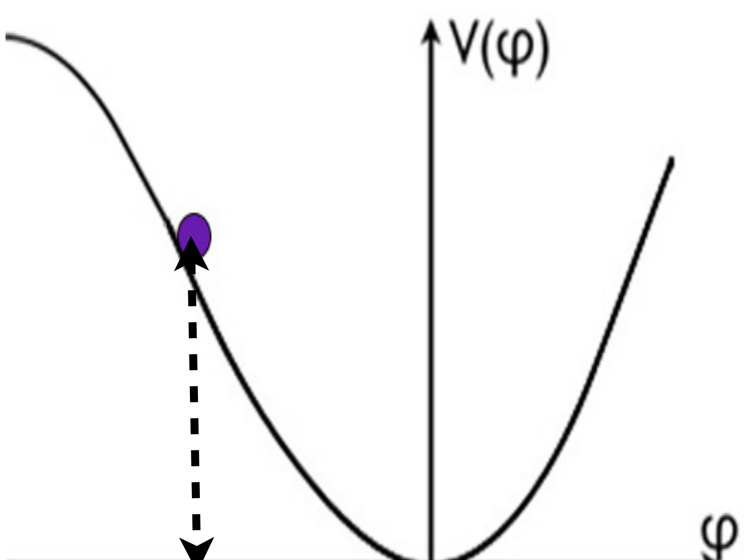
- Cosmic Inflation solves horizon, homogeneity, isotropy, flatness, relic problems, etc.



e.g. Cosmic Microwave Background homogeneous and isotropic at large distances

- "Slowly-rolling scalar (inflaton)" derives inflation and reheats the universe.

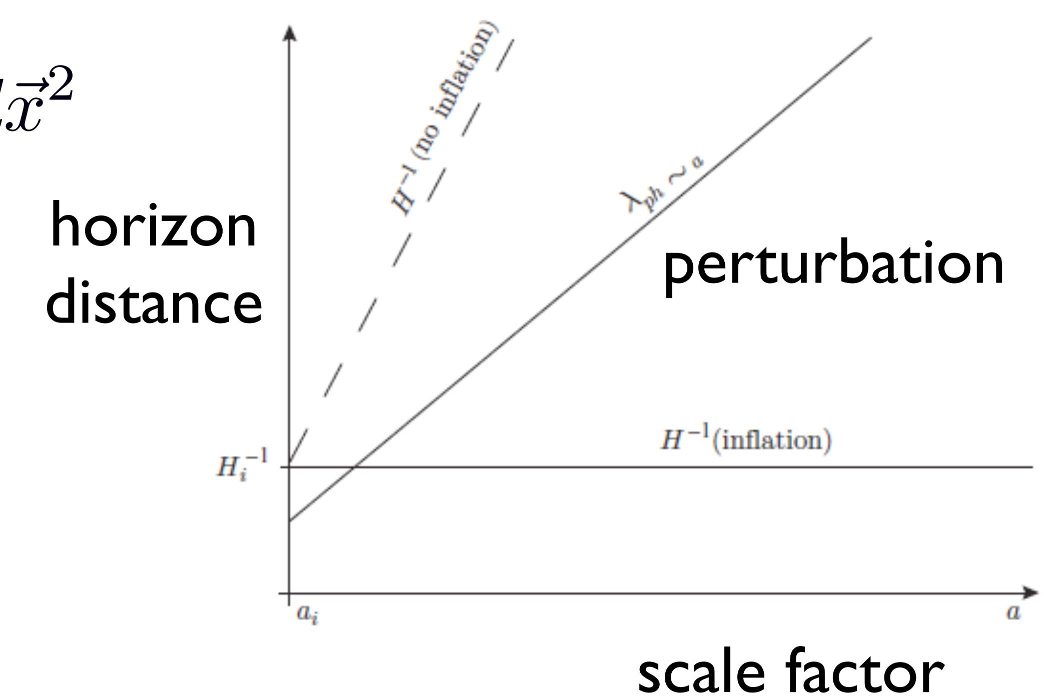
CMB anisotropies, galaxies, clusters.



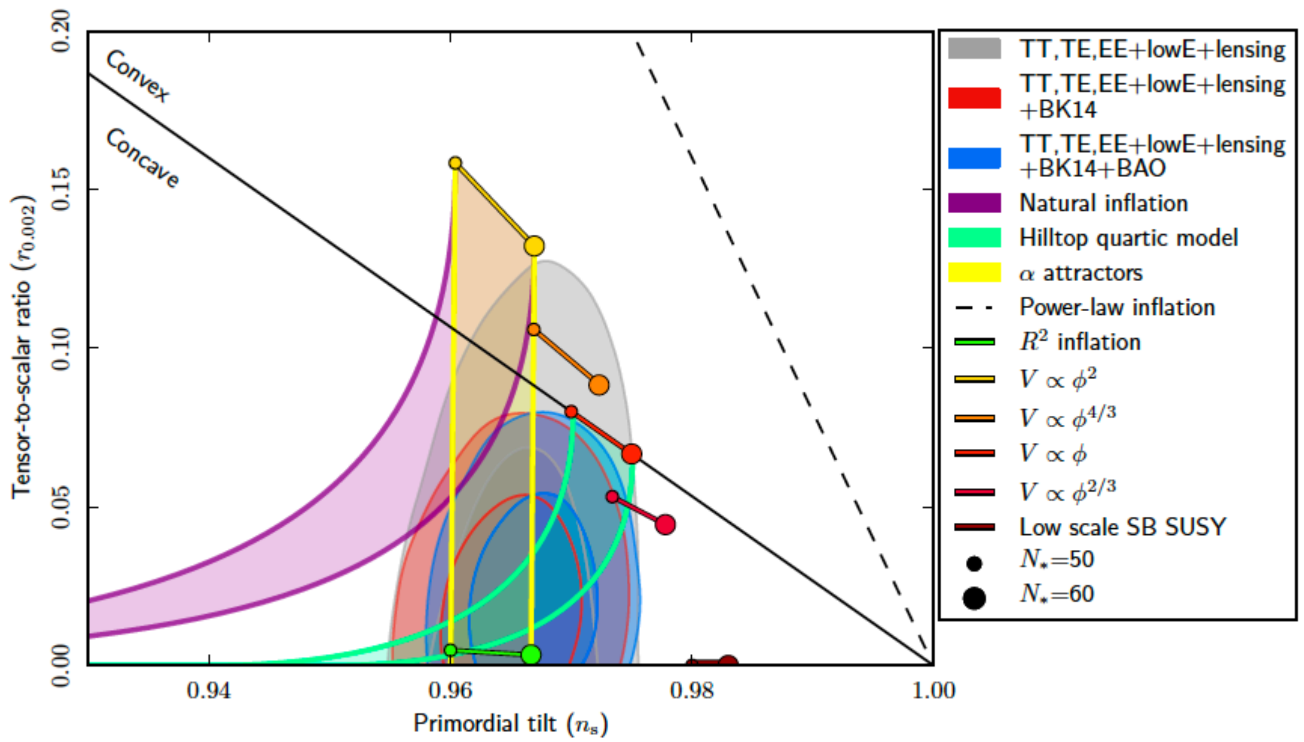
$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2$$

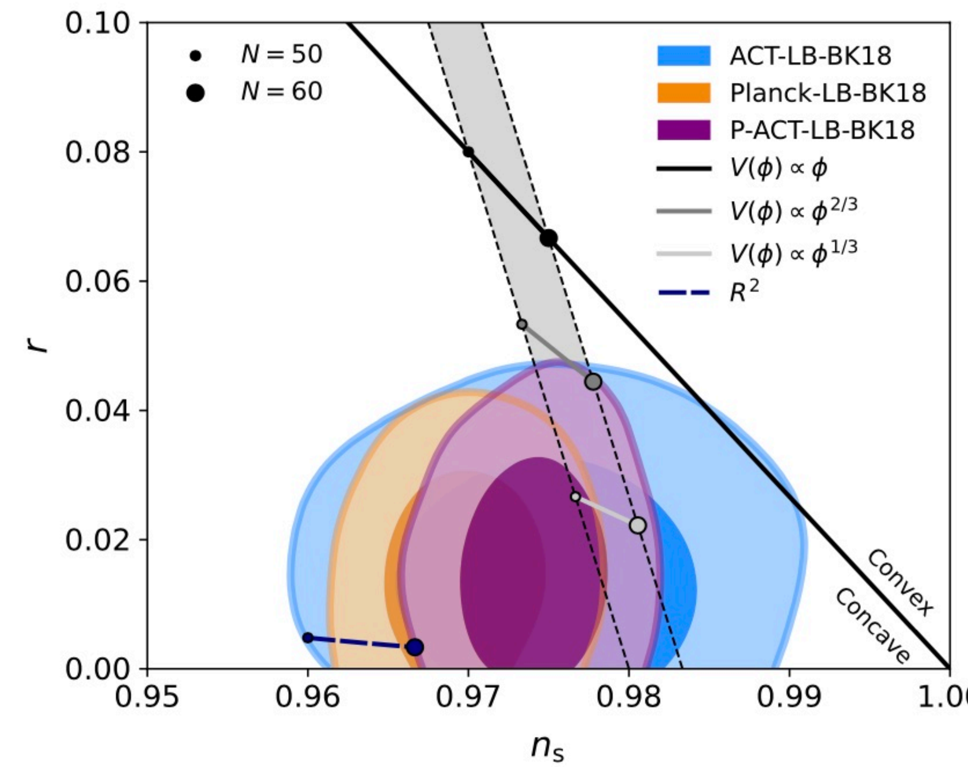
$$e^N = \frac{a_{\rm end}}{a_*},$$

$$N \approx 60.$$



Planck vs ACT





n_s=0.9665±0.0038 [Planck18+BAO] n_s=0.9709±0.0038 [Planck+ACT]

- Almost scale-invariant CMB → slow-roll inflations

$$\langle \mathcal{R}(\vec{k})\mathcal{R}(\vec{k}')\rangle = \delta^3(\vec{k}-\vec{k}')\,\frac{2\pi^2}{k^3}\mathcal{P}_{\mathcal{R}}(k), \qquad \mathcal{P}_{\mathcal{R}}(k) \propto k^{n_s-1},$$

$$n_s = 1 - 6\epsilon + 2\eta, \qquad \epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1,\ \eta = M_P^2\frac{V''}{V} \ll 1.$$

- Tensor perturbation: $r = 16\epsilon$, r<0.035 [Planck18+BK18+BAO]
- Atacama Cosmology Telescope(2025) closer to scale invariance

Starobinsky model

- Starobinsky-like models are a best fit to Planck data.

$$n_s = 1 - \frac{2}{N},\ r = \frac{12}{N^2}:$$ successful for N=40-80 at 95% C.L.

- Starobinsky model based on “pure gravity” is dual to a scalar-tensor theory.

[Starobinsky (1984)]

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{2} + \xi^2 R^2\right) \Longleftrightarrow \mathcal{L} = \sqrt{-g}\left(\frac{R}{2} + 2\xi\phi R - \phi^2\right)$$

$$\Longrightarrow \quad \mathcal{L}_E = \sqrt{-g_E}\left(\frac{R}{2} - \frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{16\xi^2}\left(1 - e^{-\sqrt{\frac{2}{3}}|\chi|}\right)^2\right)$$

Canonical kinetic terms

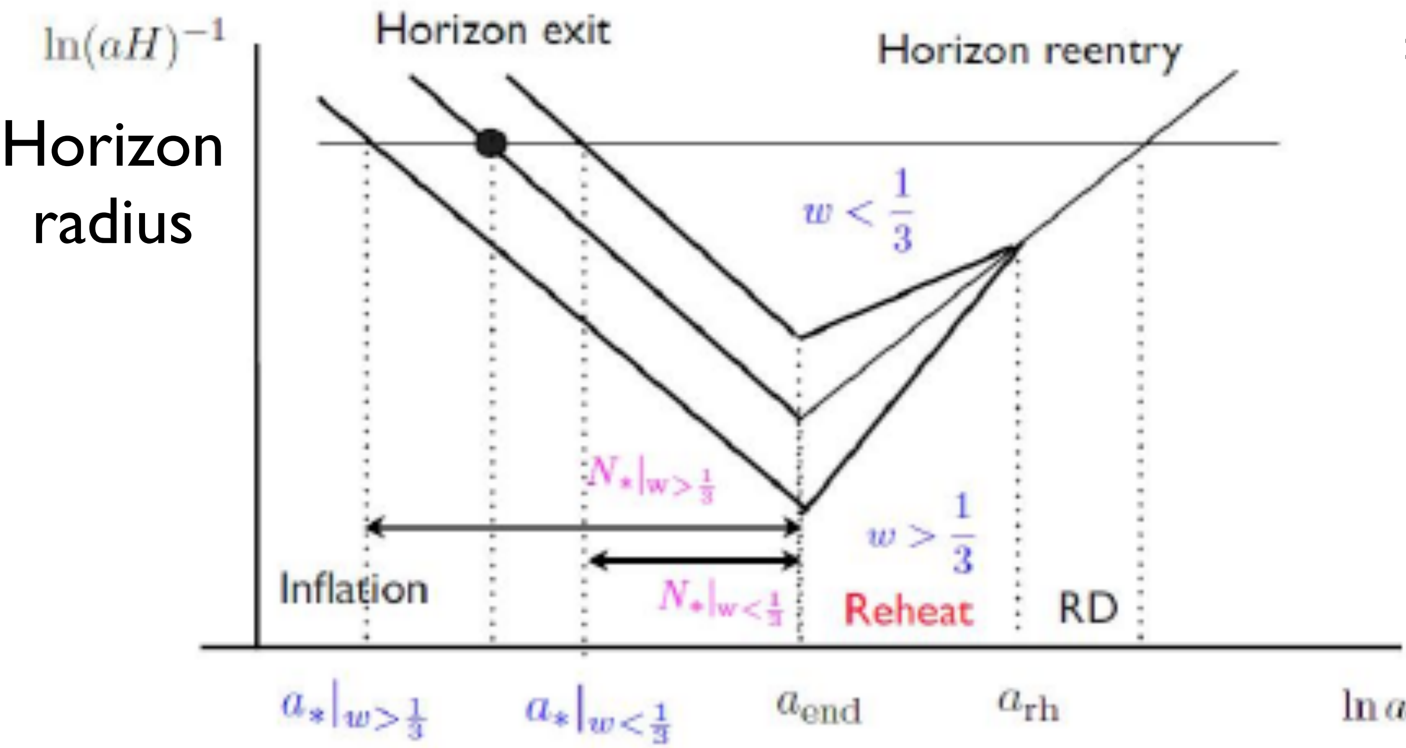
$$g_{\mu\nu} \to g_{\mu\nu}/(1+4\xi\phi) \quad 1 + 4\xi\phi = e^{\sqrt{\frac{2}{3}}|\chi|}$$

One-parameter, $\xi \sim 10^4$

Successful for Planck.

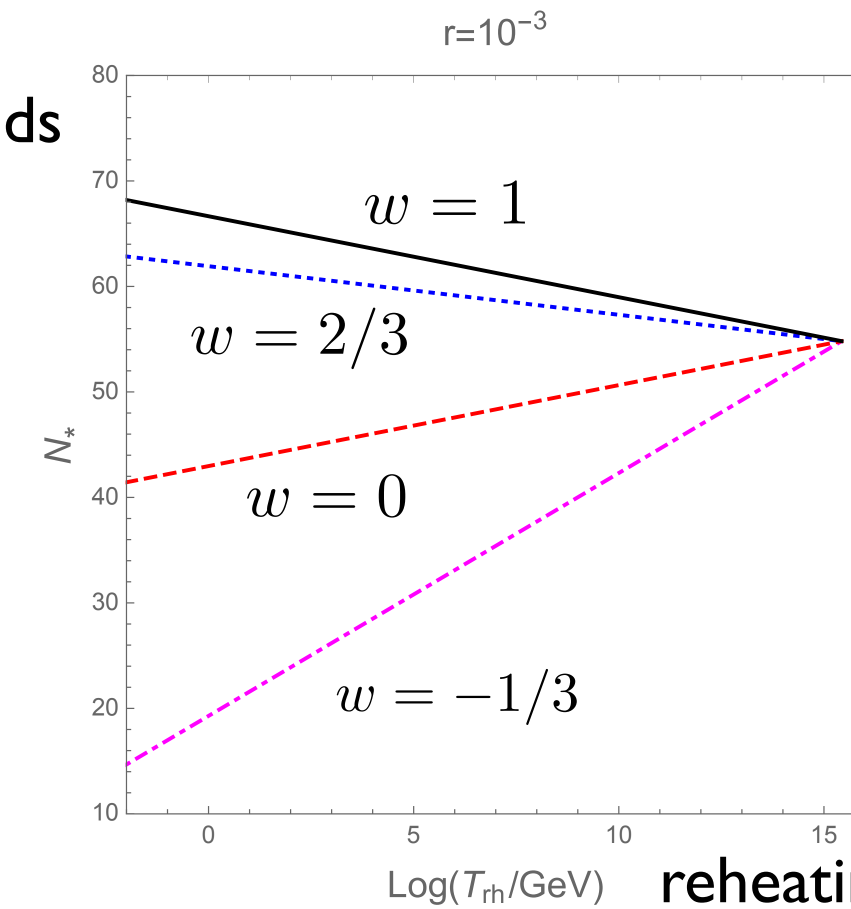
Reheating and e-folds

Horizon radius



scale factor

\# e-folds



reheating

$$\ln(aH)^{-1}_{\rm rh} \sim \frac{1}{2}(1+3w)\ln a,$$

w: equation of state

[S.-M. Choi, HML (2016)]

The number of e-foldings for solving the horizon problem is subject to the details of reheating dynamics.

$$N_* = 61.4 + \frac{3w-1}{12(1+w)} \ln\left(\frac{45}{\pi^2}\frac{V_*}{g_*(T_{\rm rh})T^4_{\rm rh}}\right) - \ln\left(\frac{V_*^{1/4}}{H_*}\right).$$

"Larger N" for ACT favors w>1/3 & low reheating.

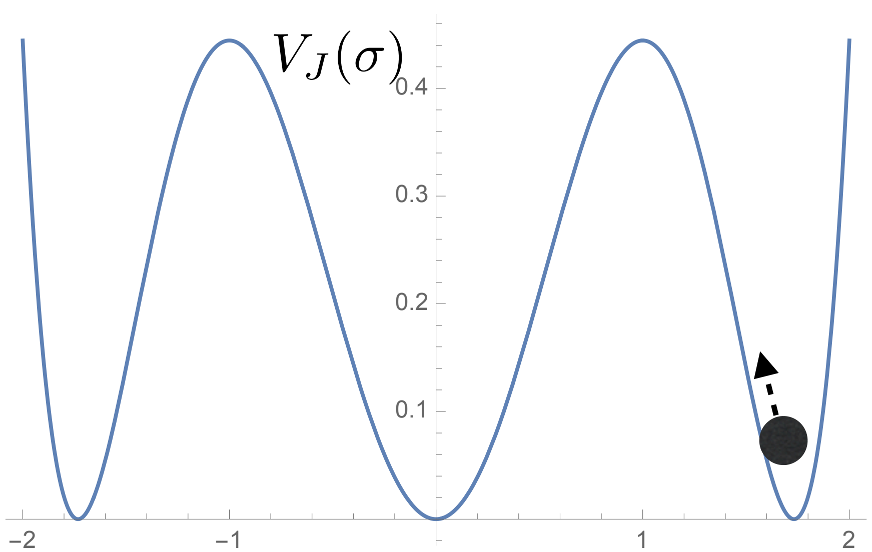
Pole inflation

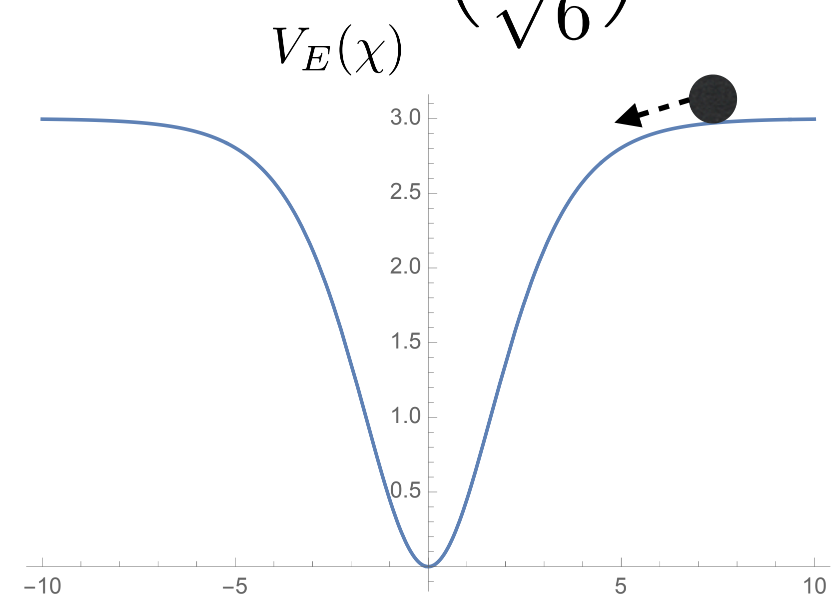
- Singlet scalar field σ with a conformal coupling:

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2}\left(1-\frac{1}{6}\sigma^2\right)R + \frac{1}{2}(\partial_\mu\sigma)^2 - V_J(\sigma)\,, \quad V_J = \beta_n\sigma^n\left(1-\frac{1}{6}\sigma^2\right)^2$$

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}R + \boxed{\frac{1}{2}\frac{(\partial_\mu\sigma)^2}{\left(1-\frac{1}{6}\sigma^2\right)^2}} - \beta_n\sigma^n$$

$$= -\frac{1}{2}R + \frac{1}{2}(\partial_\mu\chi)^2 - 6^{n/2}\beta_n\tanh^n\left(\frac{\chi}{\sqrt{6}}\right)$$





Similar predictions as in Starobinsky model.

Flat potential near the pole.

e.g. Kallosh, Linde, Roest (2013)

Pole inflation and particle physics

Higgs pole inflation

- Consider the Higgs field near conformal coupling:

Jordan-frame: $$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2}M_P^2\,\underline{\Omega(H)}R(g_J) + |D_\mu H|^2 - \underline{V_J(H)}$$

$\Omega = 1 - \frac{1}{3M_P^2}|H|^2$: "conformal coupling" [S. Clery, HML, A. Menkara (2023)]

$V_J(H) = c_m\Lambda^{4-2m}|H|^{2m}\left(1 - \frac{1}{3M_P^2}|H|^2\right)^2$ "Jordan-frame Higgs potential"

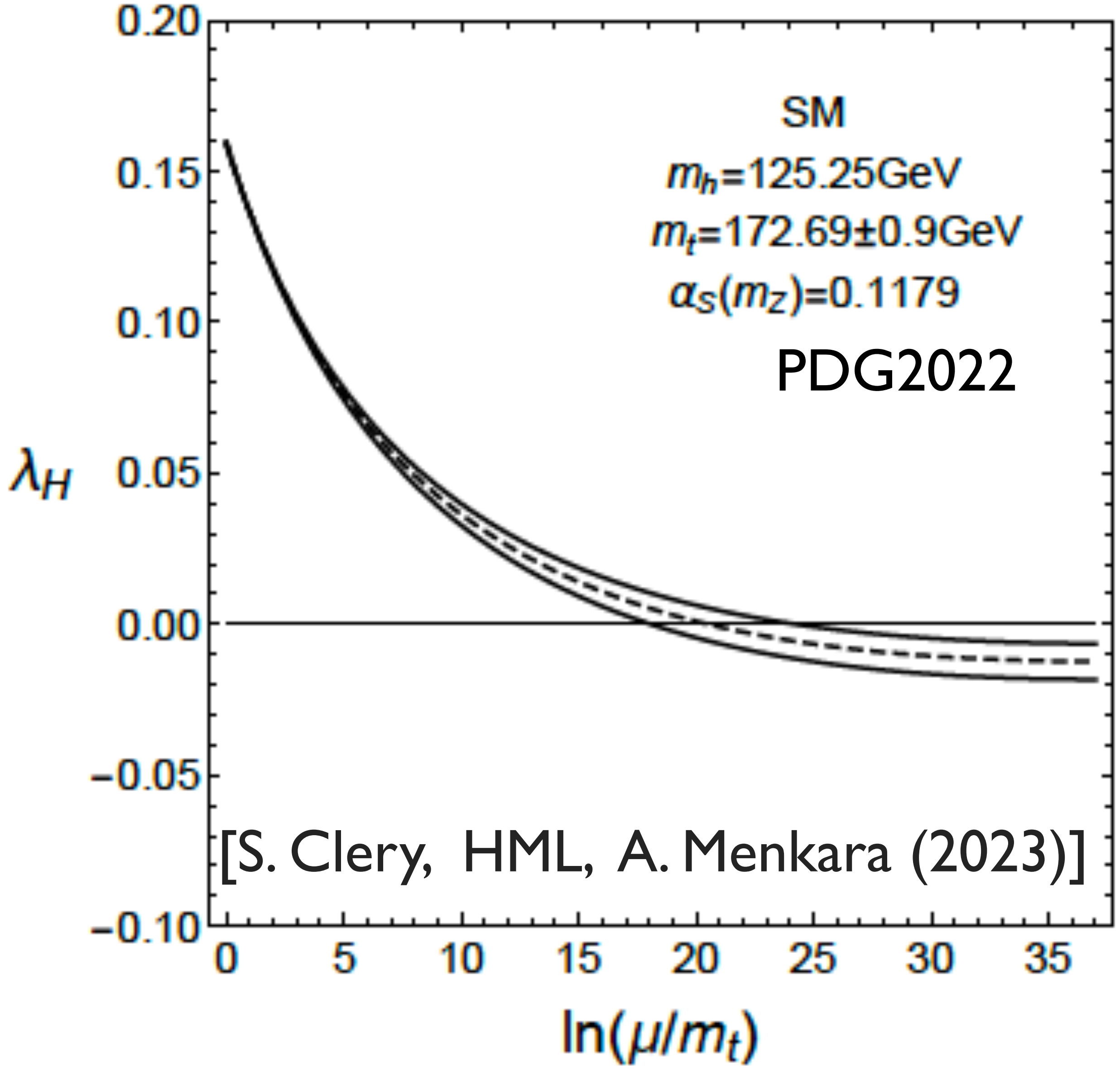
Einstein-frame: $$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}M_P^2 R(g_E) + \frac{|D_\mu H|^2}{(1-\frac{1}{3M_P^2}|H|^2)^2} - \frac{1}{3M_P^2}\left(|H|^2|D_\mu H|^2 - \frac{1}{4}\partial_\mu|H|^2\partial^\mu|H|^2\right) - \frac{V_J(H)}{(1-\frac{1}{3M_P^2}|H|^2)^2}$$

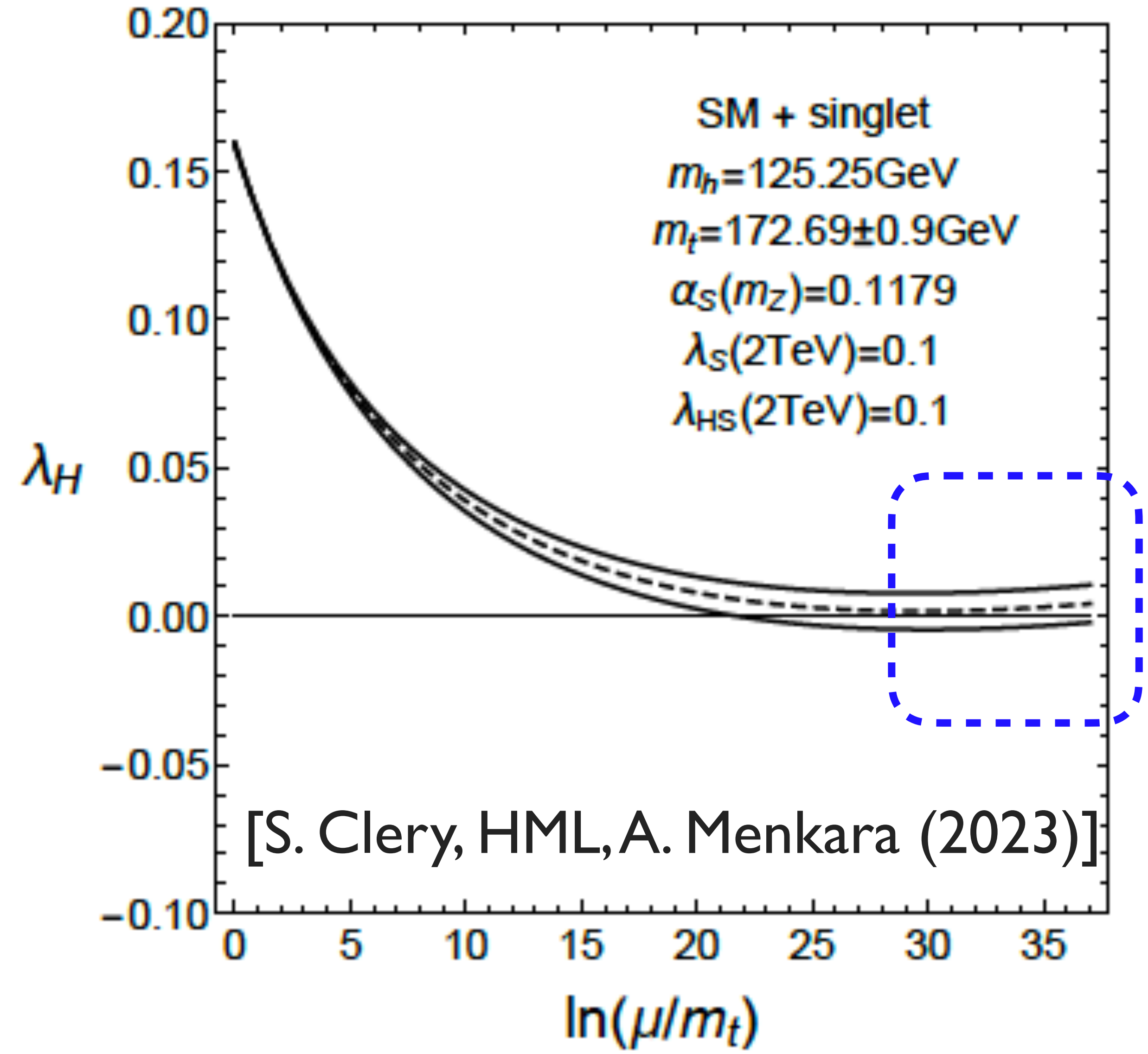
Unitary gauge: $H^T = (0,h)/\sqrt{2} \longrightarrow |H|^2|D_\mu H|^2 - \frac{1}{4}\partial_\mu|H|^2\partial^\mu|H|^2 = 0$

$$\Rightarrow \frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}M_P^2 R + \frac{1}{2}\frac{(\partial_\mu h)^2}{(1-\frac{1}{6M_P^2}h^2)^2} - \frac{c_m}{2^m}\Lambda^{4-2m}h^{2m}$$: Pole inflation type!

Small Higgs quartic coupling

- Higgs quartic coupling runs with Higgs field values.





Standard Model:

$$\lambda_H < 0 \text{ at } \mu \sim 10^{11}\,\text{GeV}$$

Up to uncertainty in top pole mass.

Add a singlet scalar:

A small positive Higgs quartic coupling achieved for inflation.

Higgs pole inflation: reheating

- Perturbative reheating from inflaton decay/scattering.

$$\dot{\rho}_\phi + 3(1+w_\phi)H\rho_\phi \simeq -\Gamma_\phi(1+w_\phi)\rho_\phi \ , \qquad \dot{\rho}_R + 4H\rho_R = \Gamma_\phi(1+w_\phi)\rho_\phi$$

$$\Gamma_\phi = \sum_f \Gamma_{\phi\to f\bar{f}} + \sum_{V=W,Z} \Gamma_{\phi\phi\to VV}$$ => suppressed for heavy particles (t, W, Z)

[S. Clery, HML, A. Menkara (2023)]

m	$T_{\rm RH}$ [GeV]
1	5.1×10^{13}
2	2.6×10^{9}
3	260
4	9.4×10^{5}
5	2.1×10^{7}
6	1.1×10^{8}
7	2.8×10^{8}
8	4.9×10^{8}
9	8.4×10^{8}
10	1.2×10^{9}

$$m\geq 2\ ,\ w_\phi = \frac{m-1}{m+1} \geq \frac{1}{3}$$

$\Delta N_{\rm reh} > 0$

Low reheating

→ favored for ACT

But, Preheating might be also important!

[HML, A. Menkara, J.-H, Yoon, work in progress]

Peccei-Quinn pole inflation

- Consider a complex singlet scalar field with PQ charge:
  "radial mode" => inflaton, "angular mode" => axion

$$\Phi = \frac{1}{\sqrt{2}}\phi\, e^{i\theta}$$

Similar results for KSVZ or DFSZ models

[HML, A. Menkara, M-J, Seung, J-H, Song (2023, 2024)]

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2}M_P^2\,\Omega(\Phi)R(g_J) + |\partial_\mu\Phi|^2 - \Omega^2(\Phi)V_E(\Phi)$$

$$\Omega(\Phi) = 1 - \frac{1}{3M_P^2}|\Phi|^2,$$

Conformal coupling to gravity

$$V_E(\Phi) = V_0' + \frac{\beta_m}{M_P^{2m-4}}|\Phi|^{2m} - m_\Phi^2|\Phi|^2 + \left(\sum_{k=0}^{[n/2]}\frac{c_k}{2M_P^{n-4}}|\Phi|^{2k}\Phi^{n-2k} + \text{h.c.}\right)$$

PQ symmetry $f_a = (m_\Phi^2 M_P^{2m-4}/\beta_m)^{1/(2m-2)}$

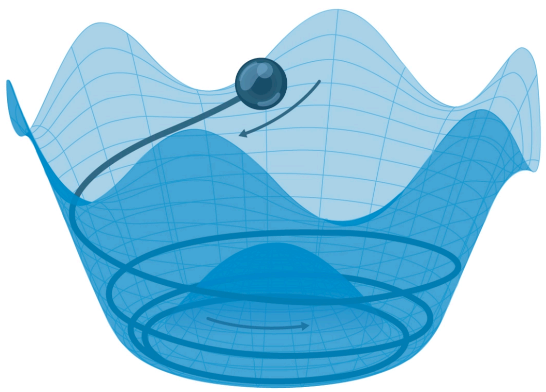
$3^m\beta_m = 1.0\times 10^{-10}$

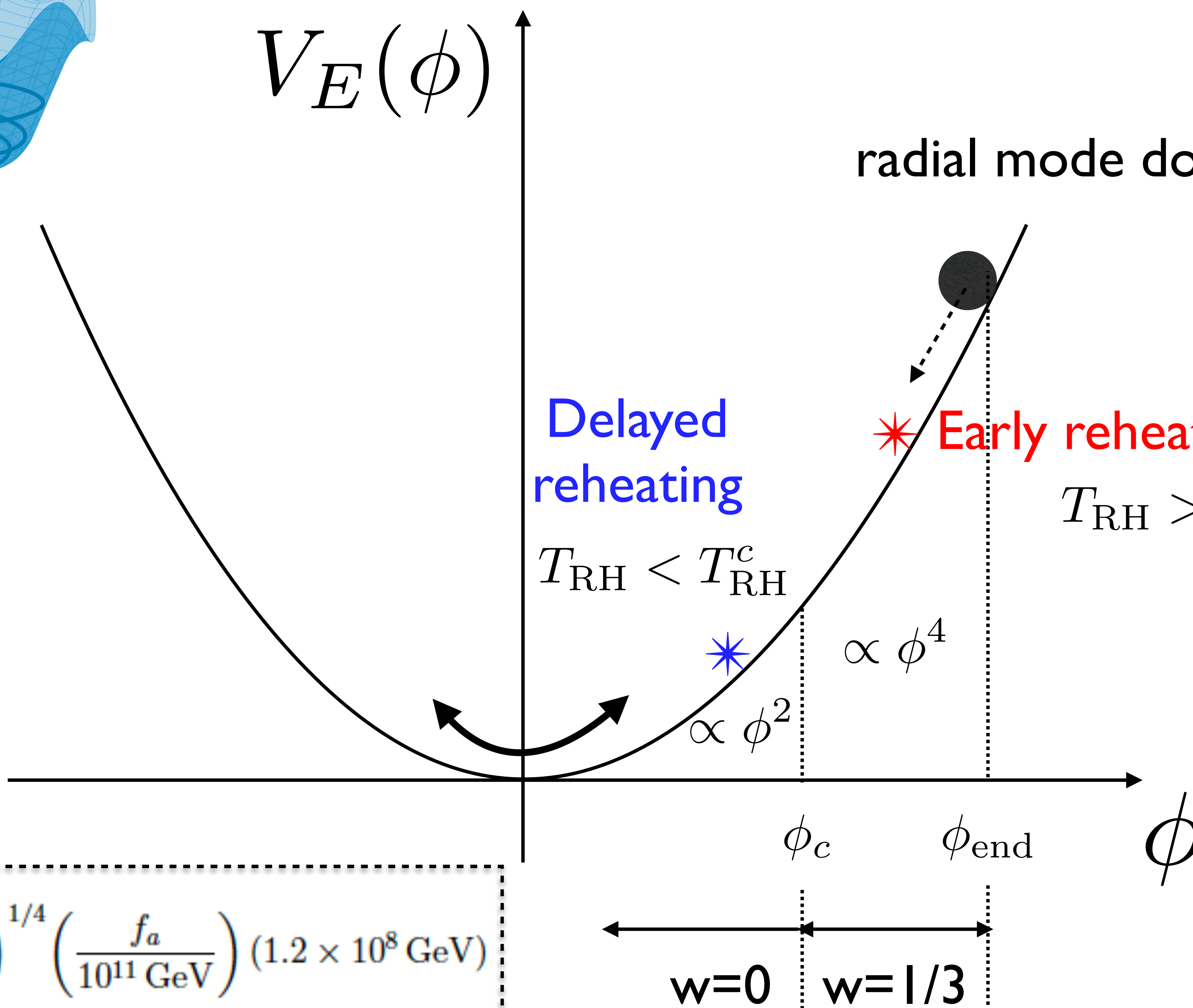
No PQ $3^{n/2}|c_k| \lesssim 10^{-10}$

PQ inflation

Axion kinetic misalignment

PQ field dynamics



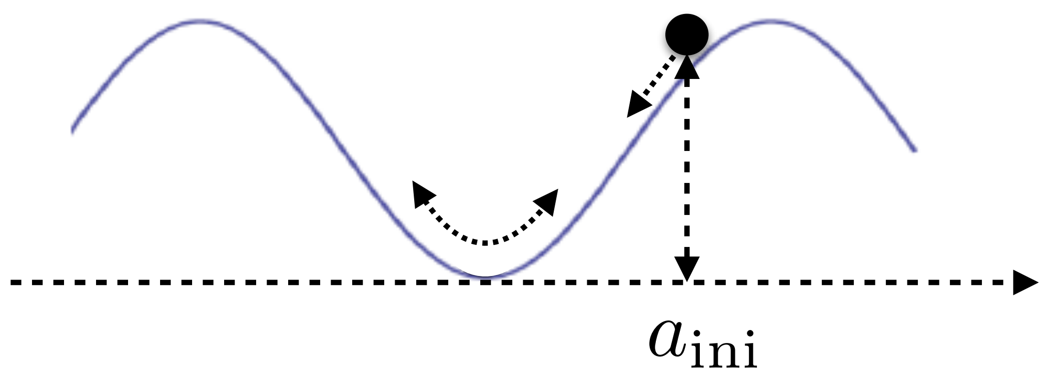


$$T^c_{\rm RH} = \left(\frac{100}{g_*}\right)^{1/4}\left(\frac{f_a}{10^{11}\,{\rm GeV}}\right)(1.2\times 10^8\,{\rm GeV})$$

Axion misalignment

- Axion abundance for dark matter is determined by the initial misalignment before QCD phase transition.

[Preskill et al; Abbott et al; Dine et al (1983)]



"Axion misalignment mechanism"

$m_a \simeq 3H$: coherent oscillation

⟶ Axion cold dark matter

Axion abundance:

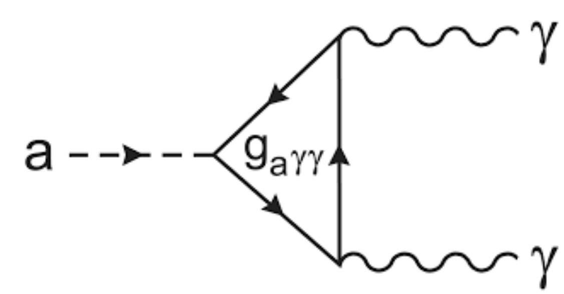
$$\Omega_a h^2 = \frac{\rho_a(a_{\rm ini})}{\rho_c/h^2}\frac{m_a(0)}{m_a(T_{\rm osc})}\left(\frac{g_{s*}(T_0)}{g_{s*}(T_{\rm osc})}\right)^{1/3}\left(\frac{T_0}{T_{\rm osc}}\right)^3$$

$$\simeq 0.12\left(\frac{f_a}{9\times 10^{11}\,{\rm GeV}}\right)^{1.165}\left(\frac{a_{\rm ini}}{f_a}\right)^2$$

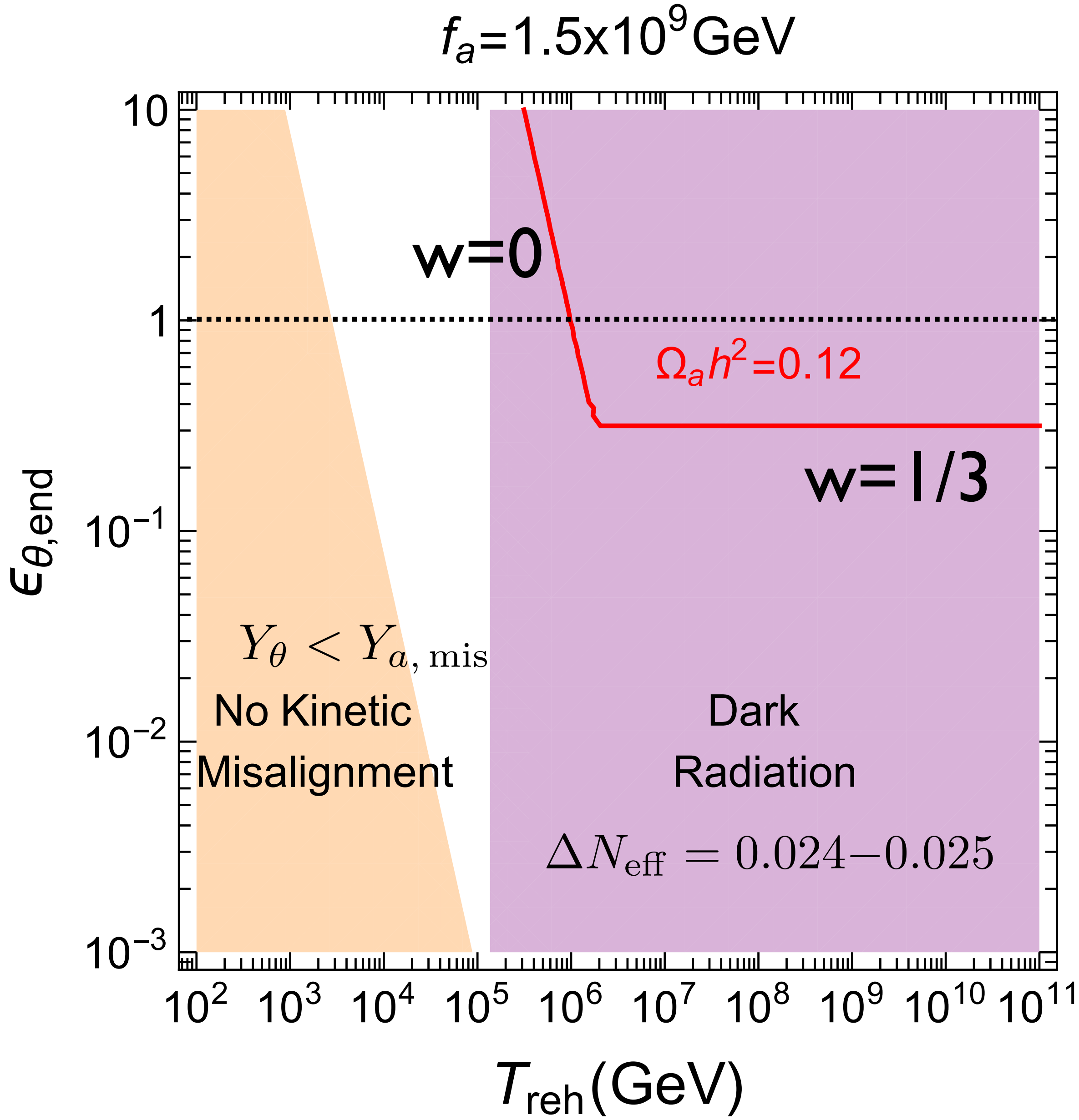
Axion window:

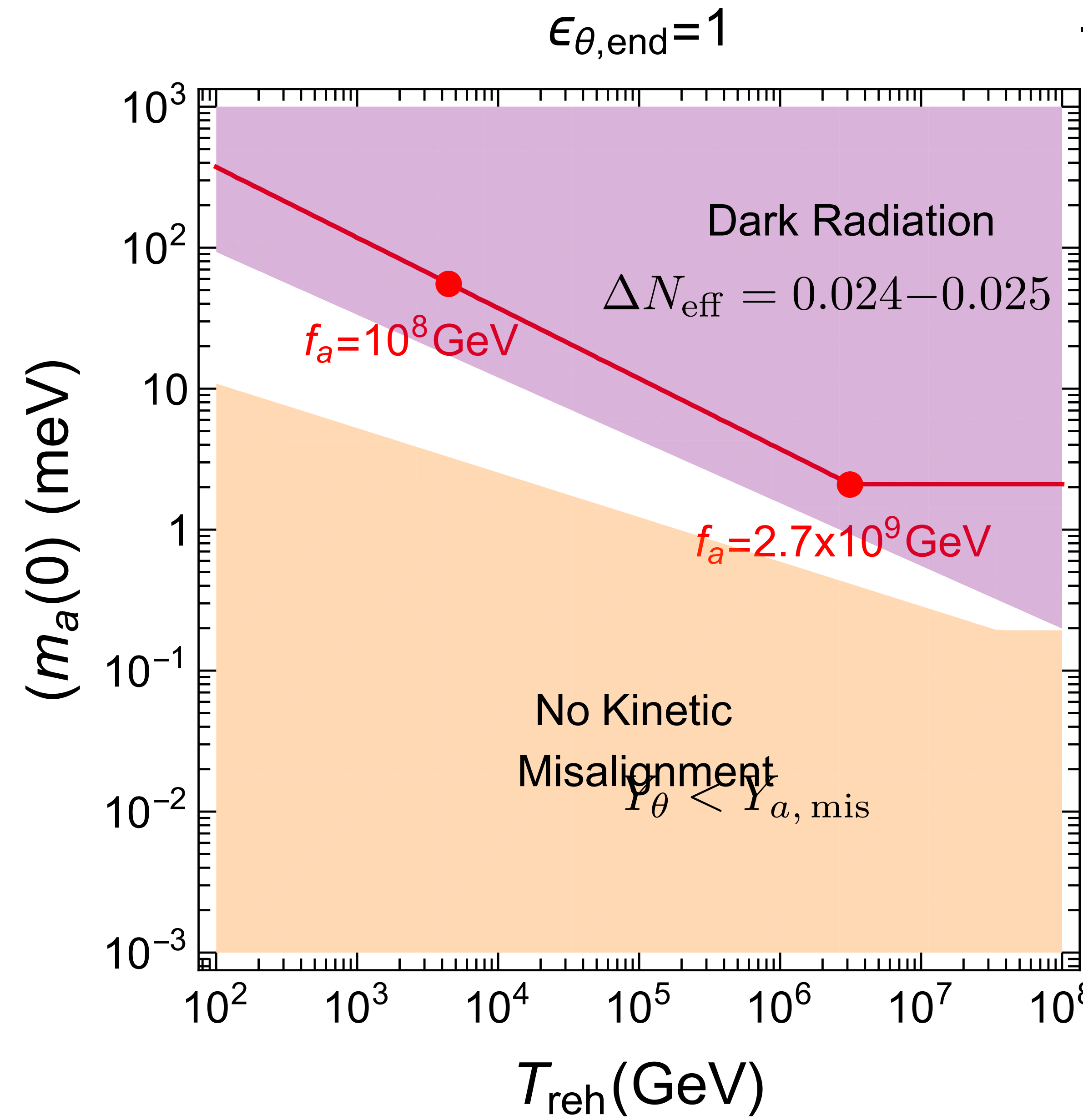
$$\underline{10^8\,{\rm GeV}} < f_a < \underline{10^{12}\,{\rm GeV}}$$

Supernova — Relic density



Axion velocity vs relic density





[HML, A. Menkara, M-J, Seung, J-H, Song (2023)]

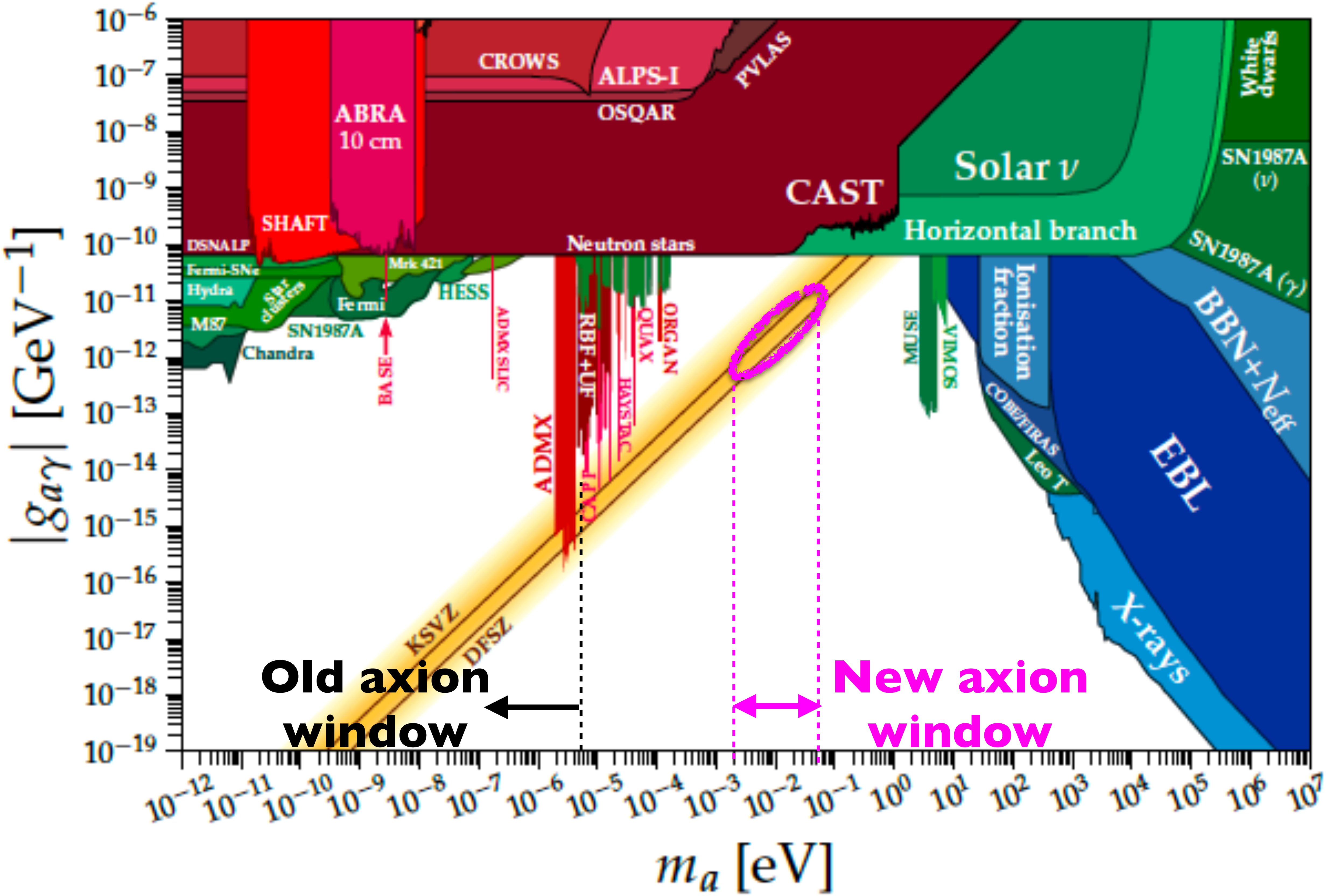
$$\epsilon_\theta \equiv \frac{M_P^2}{2V_E^2}\left(\frac{\partial V_E}{\partial \theta}\right)^2 \longrightarrow Y_\theta = \frac{n_\theta(T_{\rm RH})}{s(T_{\rm RH})} \longrightarrow \Omega_a h^2 = 0.12\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)\left(\frac{Y_\theta}{40}\right)$$

$$n_\theta = f_a^2\dot\theta$$

Axion velocity at inflation

Axion abundance at present

New axion DM window



Pole inflation in Weyl gravity

Pole inflation in Weyl gravity

- With local Weyl symmetry and global SO(1,1):

χ : dilaton, w_μ : Weyl gauge field [HML(2024)]

Weyl transform: $g_{\mu\nu} \to e^{2\alpha(x)} g_{\mu\nu}, \quad \chi \to e^{-\alpha(x)}\chi, \quad \sigma \to e^{-\alpha(x)}\sigma, \quad w_\mu \to w_\mu - \frac{1}{g_w}\partial_\mu \alpha(x)$

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = (1+a)\Big[-\frac{1}{12}(\chi^2-\sigma^2)R - \frac{1}{2}(\partial_\mu\chi)^2 + \frac{1}{2}(\partial_\mu\sigma)^2\Big]$$
$$+\frac{1}{2}a(D_\mu\chi)^2 - \frac{1}{2}a(D_\mu\sigma)^2 - \frac{1}{4}w_{\mu\nu}w^{\mu\nu} - V(\chi,\sigma),$$

$$D_\mu\chi = (\partial_\mu - g_w w_\mu)\chi, \quad D_\mu\phi_i = (\partial_\mu - g_w w_\mu)\phi_i, \quad V(\chi,\sigma) = F(\sigma^2/\chi^2)(\chi^2-\sigma^2)^2$$

Gauge fixing: $\langle\chi\rangle = \sqrt{\frac{6}{1+a}}$ → Generation of Planck scale & Weyl photon mass

$F(\sigma^2/\chi^2) = \frac{\alpha_n}{\langle\chi^4\rangle}\left(\frac{\sigma}{\chi}\right)^n$ → SO(1,1) breaking: slow-roll inflation

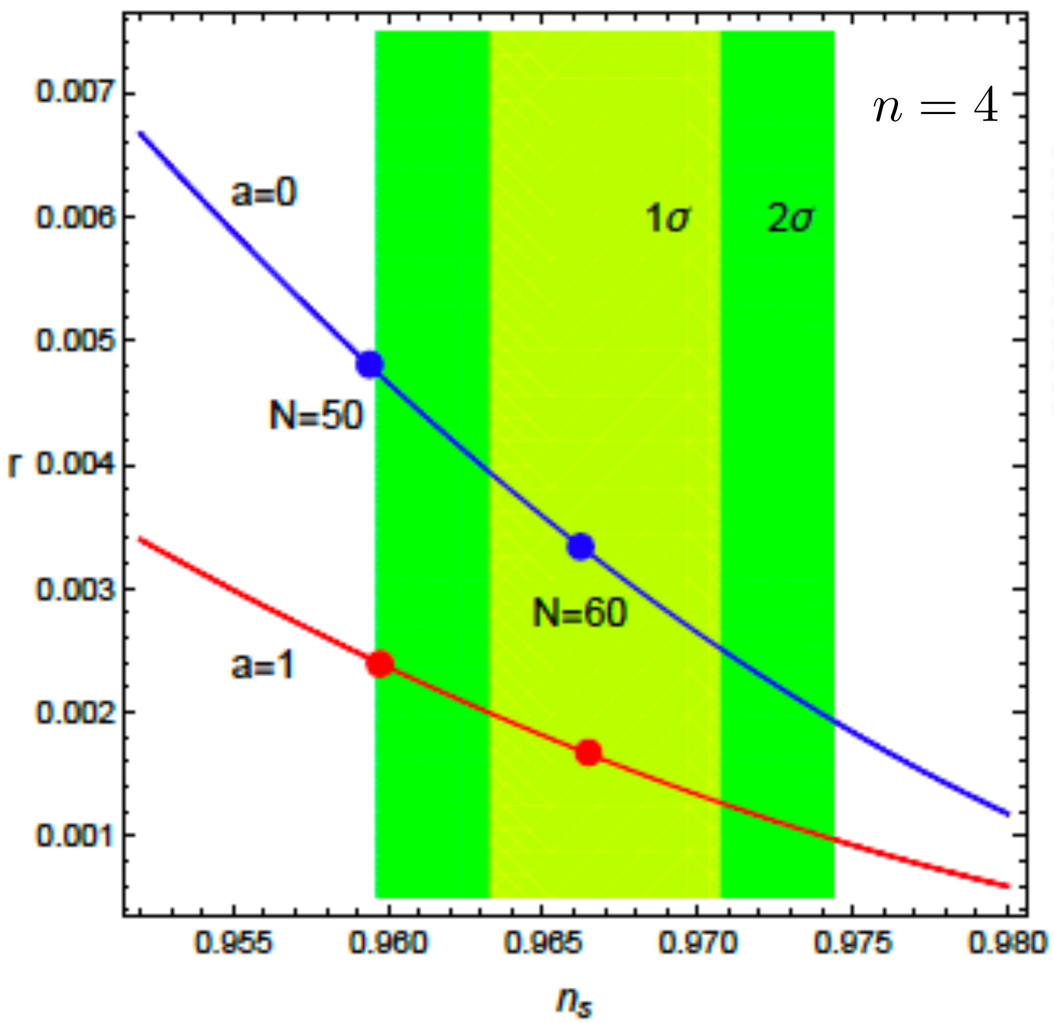
Generalized pole inflation

- Gauge-fixed Lagrangian in Einstein frame:

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}R + \frac{1}{2}\frac{(\partial_\mu\sigma)^2}{\left(1-\frac{1}{6}(1+a)\sigma^2\right)^2} - V_E(\sigma) - \frac{1}{4}\widetilde{w}_{\mu\nu}\widetilde{w}^{\mu\nu} + \frac{1}{2}m_w^2\widetilde{w}_\mu\widetilde{w}^\mu,$$

$$V_E(\sigma) = F(\sigma^2/\langle\chi^2\rangle) = \beta_n\sigma^n, \qquad \beta_n = \frac{\alpha_n}{\langle\chi^n\rangle}$$

redefined field



[HML(2024)]

Pole inflation and Weyl photon mass:

$$n_s \simeq 1 - \frac{2}{N}, \quad r \simeq \frac{12}{(1+a)N^2}, \quad m_w^2 = \frac{6ag_w^2}{1+a}M_P^2$$

General isometry SO(1,N):

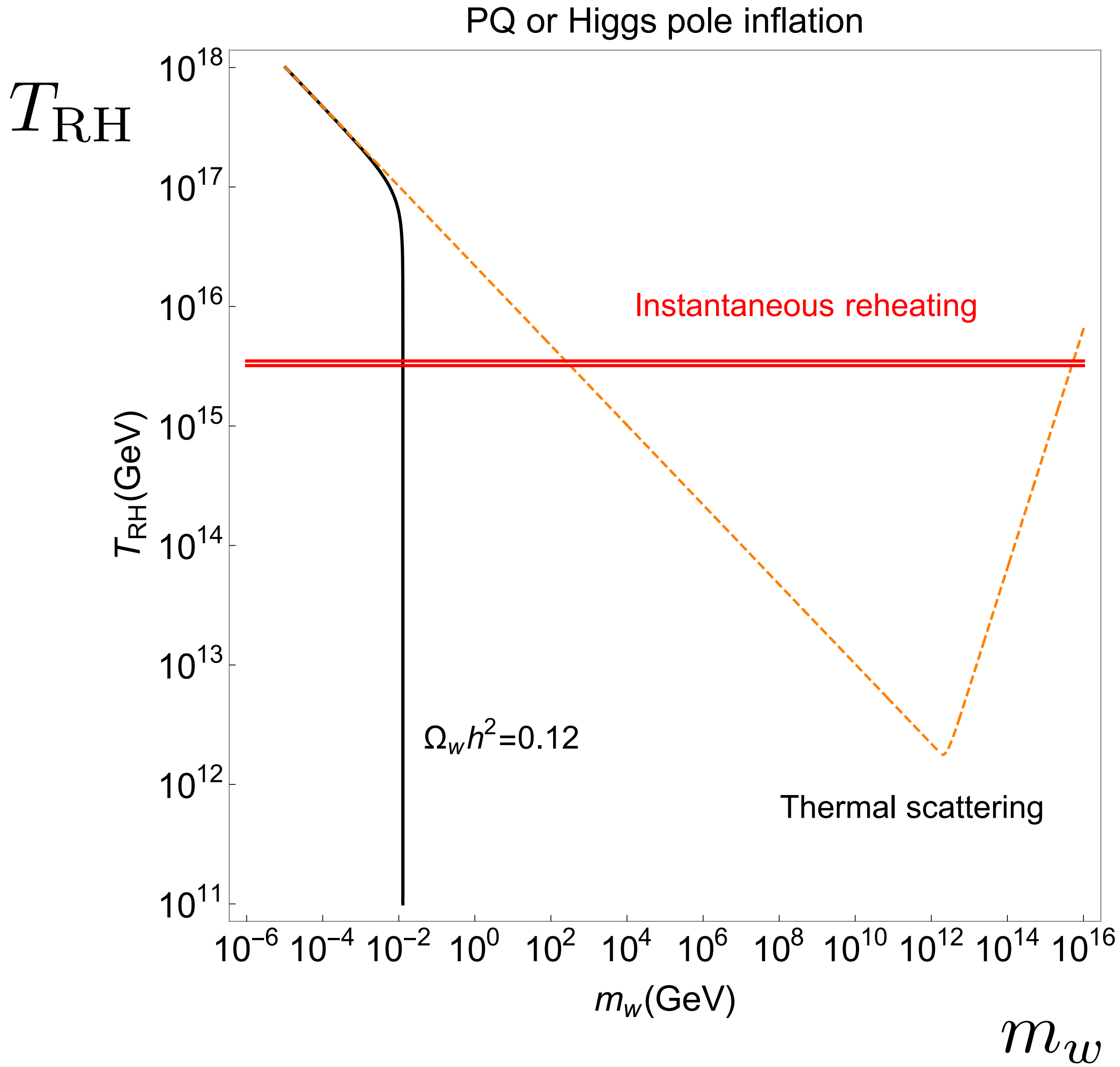
$$\sigma \longrightarrow \phi_i, \ i = 1, 2, \cdots, N,$$

- N=4: Higgs pole inflation,
- N=2: PQ pole inflation.

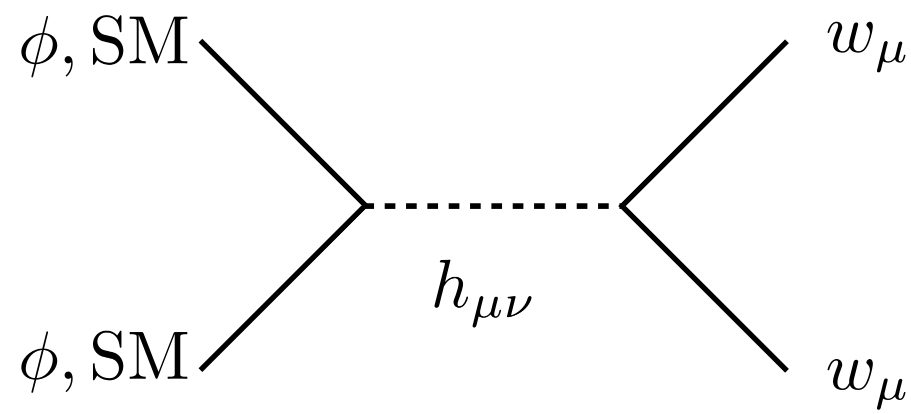
Weyl photon dark matter

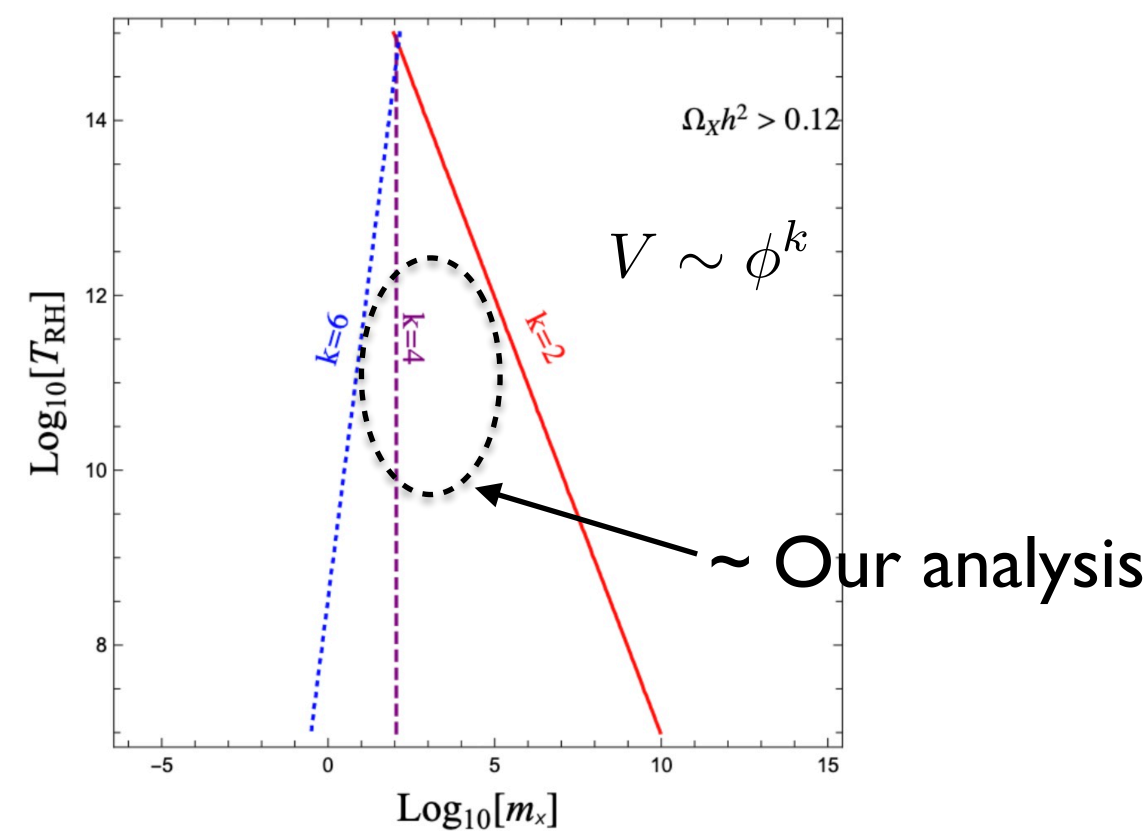
- Gravitational production of Weyl photons by SM-SM scattering or inflaton scattering during reheating.

DM: $m_w \simeq 10\,\mathrm{MeV}$



[HML(2024)]





Scalar DM => [S. Clery et al (2021)]

Conclusions

- The pole inflation relies on a conformal coupling to gravity and a small quartic coupling of the inflaton, leading to successful & testable predictions.
- SM Higgs or PQ fields can be realized when the running quartic coupling for the inflaton remains small during inflation, restricting the inflaton couplings in the RG equations for SM and BSM.
- Axion kinetic misalignment set during the PQ pole inflation opens up a new window for axion DM with a small axion decay constant.
- Broken SO(1,N) isometry in Weyl gravity realizes the pole inflation and relates between Weyl photon mass and inflationary predictions.